

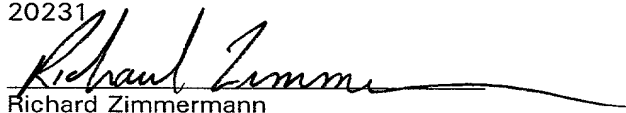
JOINT INVENTORS

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Richard Zimmermann

APPLICATION FOR UNITED STATES LETTERS PATENT

S P E C I F I C A T I O N

TO ALL WHOM IT MAY CONCERN:

Be it known that we, Geun Su Lee, a citizen of the Republic of Korea, residing at #103-302 Samick Apt., Bubal-eub, Shinha-ri, Ichon-shi, Kyongki-do 467-860, Republic of Korea, and Jae Chang Jung, a citizen of the Republic of Korea, residing at #107-1304 Hyundai Apt., Sadong-ri, Daewol-myeon, Ichon-shi, Kyongki-do 467-850, Republic of Korea, and Ki Soo Shin, a citizen of the Republic of Korea, residing at #307-1301 Kisan Apt., Yatop-2-dong, Bundang-gu, Sungham-shi, Kyongki-do 463-070, Republic of Korea, have invented a new and useful PHOTORESIST MONOMERS, POLYMERS THEREOF AND PHOTORESIST COMPOSITIONS CONTAINING THE SAME, of which the following is a specification.

PHOTORESIST MONOMERS, POLYMERS THEREOF AND
PHOTORESIST COMPOSITIONS CONTAINING THE SAME

BACKGROUND

5 Technical Field

Novel photoresist monomers, polymers thereof and photoresist compositions containing the same are disclosed. In particular, photoresist monomers suitable for a photolithography process using DUV (deep
10 ultraviolet) light sources, particularly VUV (vacuum ultraviolet : 157nm) in fabricating minute circuits for highly integrated semiconductor devices, photoresist polymers thereof and photoresist compositions containing the same, and preparation processes are also disclosed.

15

Description of the Related Art

In general, a useful photoresist for ArF and VUV has a variety of desired characteristics, such as low light absorbance at the wavelength of 193nm and 157nm,
20 excellent etching resistance, and excellent adhesiveness to a wafer. In addition, a photoresist should be easily developable in a commercially readily available developing solution, such as 2.38wt% and 2.6wt% aqueous tetramethylammonium hydroxide (TMAH) solution.

25 Recently, much research has been conducted on resins having a high transparency at the wavelength of 248nm and 193nm and dry etching resistance similar to novolac resin. However, most of these photoresists are not suitable for VUV due to their poor transmittance at 157nm wavelength.

30 In order to solve the problem, research on polyethylene or polyacrylate containing fluorine has been performed. As an example, a tetrafluoroethylene as a monomer has been studied by DuPont. Tetrafluoroethylene

is difficult to control and handle effectively when it is polymerized with other comonomers since it exists in gaseous phase. Therefore it yields inconsistent rates of polymerization.

5

SUMMARY OF THE DISCLOSURE

Accordingly, novel photoresist monomers, polymers thereof and photoresist compositions containing the same are disclosed that can be used for a light sources such

10

as ArF (193nm) and VUV (157nm). Processes for forming a photoresist pattern using the photoresist compositions described above and semiconductor elements produced by using the process described above are also disclosed.

15

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a photograph of a photoresist pattern obtained in Example 5;

Figure 2 is a photograph of a photoresist pattern obtained in Example 6;

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Figure 3 is a photograph of a photoresist pattern obtained in Example 7;

Figure 4 is a photograph of a photoresist pattern obtained in Example 8; and

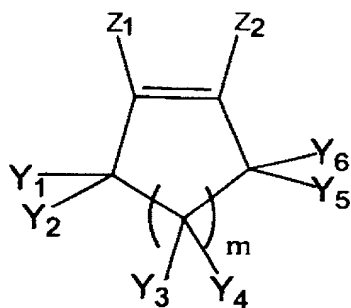
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Figure 5 is a VUV spectrum for a photoresist composition obtained in Example 8.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

First of all, novel photoresist monomers are represented by following Formula 1:

5 Formula 1



wherein Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Z₁ and Z₂ individually represent halogen or alkyl partially or wholly substituted with halogen; and

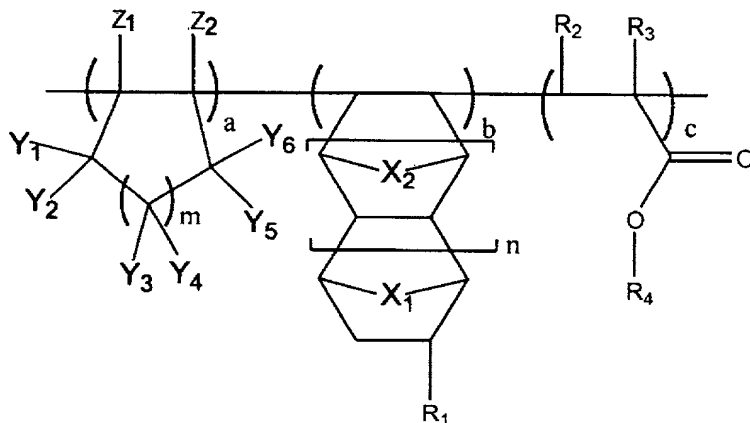
10 m is an integer ranging from 0 to 2.

Preferably, Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Z₁ and Z₂ are individually F, Cl, Br, I or CF₃.

Some of preferred photoresist monomers are octafluorocyclopentene or hexafluorocyclobutene.

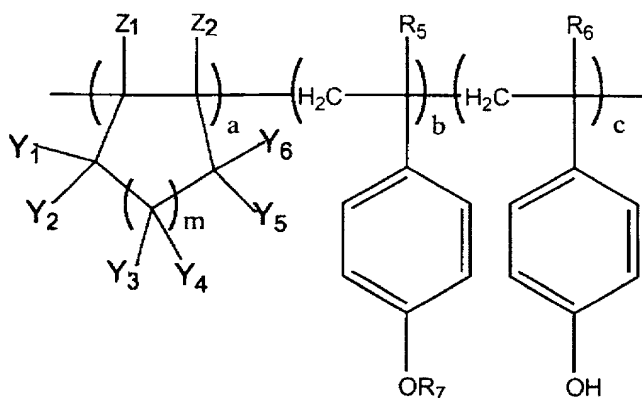
15 In addition, photoresist polymers comprise the compound of Formula 1 as a comonomer. The photoresist polymers also comprise a repeating unit represented by following Formula 2 or Formula 3.

Formula 2



20

Formula 3



wherein R_1 represents H, halogen, (C_1-C_{20}) alkyl, (C_1-C_{20}) alkyl with halogen substituent(s), (C_1-C_{20}) alkyl containing at least one of ether group $(-O-)$ and ester group, (C_1-C_{20}) alkyl with halogen substituent(s) and containing at least one of ether group and ester group or $-COOR'$;

R_2 , R_3 , R_5 and R_6 individually represent H, halogen, (C_1-C_{20}) alkyl, (C_1-C_{20}) alkyl with halogen substituent(s), (C_1-C_{20}) alkyl containing at least one of ether group and ester group or (C_1-C_{20}) alkyl with halogen substituent(s) and containing at least one of ether group and ester group;

R' , R_4 and R_7 are individually acid labile protecting groups;

X_1 and X_2 individually represent (C_1-C_{10}) alkylene, O or S;

Y_1 , Y_2 , Y_3 , Y_4 , Y_5 , Y_6 , Z_1 and Z_2 individually represent halogen or alkyl partially or wholly substituted with halogen;

m and n are individually integers ranging from 0 to 2; and

the ratio $a : b : c$ has the ranges 1-50mol% : 0-90mol% : 0-90mol%.

Preferably, R_2 , R_3 , R_5 and R_6 individually represent H, F, (C_1-C_{20}) alkyl, (C_1-C_{20}) perfluoroalkyl, (C_1-C_{20}) alkyl

containing at least one of ether group and ester group,
(C₁-C₂₀) perfluoroalkyl containing at least one of ether
group and ester group, (C₁-C₂₀) alkyl partially
substituted with F or (C₁-C₂₀) alkyl partially substituted
5 with F and containing at least one of ether group and
ester group; and Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Z₁ and Z₂
individually represent F, Cl, Br, I or CF₃. More
preferably, R₂, R₃, R₅ and R₆ are individually H, F, CH₃ or
CF₃.

10 And the acid labile protecting group can be any of
known protecting groups which prevent the compound from
dissolving in an alkaline developing solution. However,
under the presence of acid, the acid labile group is
substituted with acid, thereby making the compound
15 soluble to the alkaline solution.

Some of conventional acid labile protecting groups
are disclosed in US 5,212,043 (May 18, 1993), WO 97/33198
(Sep 12, 1997), WO 96/37526 (Nov 28, 1996), EP 0 794 458
(Sep 10, 1997), EP 0789 278 (Aug 13, 1997), US 6,132,926
20 (Oct 17, 2000), US 6,143,463 (Nov 7, 2000), US 6,150,069
(Nov 21, 2000), US 6,180,316 B1 (Jan 30, 2001), US
6,225,020 B1 (May 1, 2001), US 6,235,448 B1 (May 22, 2001)
and US 6,235,447 B1 (May 22, 2001). Acid labile protecting
groups are preferably selected from the group consisting
25 of 2-methyl 2-adamantyl, 2-ethyl 2-adamantyl, 8-ethyl 8-
tricyclodecanyl, tert-butyl, tetrahydropyran-2-yl, 2-
methyl tetrahydropyran-2-yl, tetrahydrofuran-2-yl, 2-
methyl tetrahydrofuran-2-yl, 1-methoxypropyl, 1-methoxy-
1-methylethyl, 1-ethoxypropyl, 1-ethoxy-1-methylethyl, 1-
30 methoxyethyl, 1-ethoxyethyl, tert-butoxyethyl, 1-
isobutoxyethyl and 2-acetylmenth-1-yl.

Some of preferred repeating units of above Formula 2
include poly(hexafluorocyclobutene/2-methyl 2-adamantyl
5-norbornene-2-carboxylate),

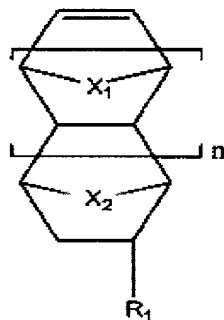
poly(octafluorocyclopentene/8-ethyl 8-tricyclodecanyl 5-norbornene-2-carboxylate) or
 poly(octafluorocyclopentene/2-methyl 2-adamantyl 5-norbornene-2-carboxylate/2-ethyl 2-adamantyl acrylate),
 5 and one of preferred repeating unit of above Formula 3 is
 poly(hexafluorocyclobutene/4-ethoxyethoxy styrene/4-hydroxy styrene).

The process for preparing a photoresist polymer comprising the repeating unit of Formula 2 or Formula 3
 10 will now be explained in more detail. The disclosed repeating unit can be prepared by radical polymerization or anion polymerization.

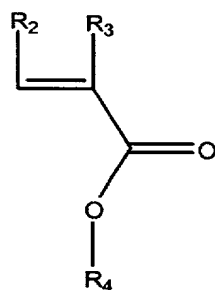
For example, the repeating unit of Formula 2 is prepared according to a process comprising:

- 15 (a) admixing (i) a monomer of Formula 1 and optionally (ii) at least one monomer selected from the group consisting of Formula 4 and Formula 5; and
 (b) adding a radical polymerization initiator into the resultant of step (a) in case of performing a radical
 20 polymerization; or adding an anion polymerization catalyst into the resultant of step (a) in case of performing an anion polymerization.

Formula 4



Formula 5



wherein R₁ represents H, halogen, (C₁-C₂₀) alkyl, (C₁-C₂₀) alkyl with halogen substituent(s), (C₁-C₂₀) alkyl containing at least one of ether group and ester group, (C₁-C₂₀) alkyl with halogen substituent(s) and containing at least one of ether group and ester group or -COOR' ;

R₂ and R₃ individually represent H, halogen, (C₁-C₂₀) alkyl, (C₁-C₂₀) alkyl with halogen substituent(s), (C₁-C₂₀) alkyl containing at least one of ether group and ester group or (C₁-C₂₀) alkyl with halogen substituent(s) and containing at least one of ether group and ester group;

R' and R₄ are individually acid labile protecting groups;

X₁ and X₂ individually represent (C₁-C₁₀)alkylene, O or S; and

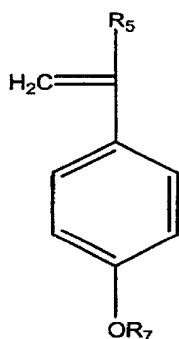
n is an integer ranging from 0 to 2.

In addition the repeating unit of Formula 3 is prepared according to a process comprising:

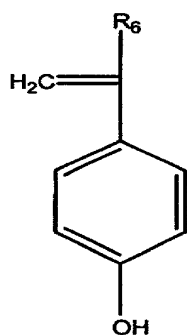
(a) admixing (i) a monomer of Formula 1 and optionally (ii) at least one monomer selected from the group consisting of Formula 6 and Formula 7; and

(b) adding a radical polymerization initiator into the resultant of step (a) in case of performing a radical polymerization; or adding an anion polymerization catalyst into the resultant of step (a) in case of performing an anion polymerization.

Formula 6



Formula 7



5 wherein R_5 and R_6 individually represent H, halogen, $(\text{C}_1\text{-C}_{20})$ alkyl, $(\text{C}_1\text{-C}_{20})$ alkyl with halogen substituent(s), $(\text{C}_1\text{-C}_{20})$ alkyl containing at least one of ether group and ester group or $(\text{C}_1\text{-C}_{20})$ alkyl with halogen substituent(s) and containing at least one of ether group and ester
10 group; and

R_7 is an acid labile protecting group.

The repeating unit of Formula 3 can be prepared according to the following process as well as polymerizing each comonomer as mentioned above. The
15 process comprises:

- (a) polymerizing a monomer of Formula 1 and 4-acetoxy styrene derivative by radical polymerization or anion polymerization;
- (b) hydrolyzing the resultant polymer of step (a) to
20 obtain a copolymer comprising the monomer of Formula 1 and 4-hydroxy styrene monomer of Formula 7; and

(c) reacting a compound containing acid labile protecting group (R_7) with the resultant of step (b) thereby substituting some hydrogens of hydroxyl group with acid labile protecting group to obtain the repeating unit of Formula 3.

In the above process, radical polymerization or anion polymerization can be carried out by bulk polymerization or solution polymerization.

The organic solvents suitable for solution polymerization can be cyclohexanone, cyclopentanone, tetrahydrofuran, dimethylformamide, dimethylsulfoxide, dioxane, methylethylketone, benzene, toluene, xylene or mixtures thereof.

Exemplary polymerization initiators include any conventional radical polymerization initiators such as 2,2'-azobisisobutyronitrile (AIBN), benzoyl peroxide, acetyl peroxide, lauryl peroxide, tert-butyl peracetate or di-tert-butyl peroxide.

And the anion polymerization catalyst include KOH, NaNH_2 , alkoxide ion, alkali metal, Grignard reagent, or alkyl lithium such as lithium diisopropyl amide or n-BuLi.

Preferably, after polymerization, the repeating unit is subject to crystallization and/or purification by using diethyl ether, petroleum ether, alkane, alcohol, water or mixtures thereof.

A photoresist polymer comprises the above repeating unit in the main chain and further comprises other comonomers or additives if necessary.

In addition, another aspect of the present invention provides a photoresist composition comprising (i) a photoresist polymer described above; (ii) a photoacid generator; and (iii) an organic solvent.

Any of conventional photoacid generator, which is able to generate acids when it is exposed to light, can

be used. Some of conventional photoacid generator are disclosed in US 5,212,043 (May 18, 1993), WO 97/33198 (Sep 12, 1997), WO 96/37526 (Nov 28, 1996), EP 0 794 458 (Sep 10, 1997), EP 0789 278 (Aug 13, 1997) and US 5 6,132,926 (Oct 17, 2000), US 6,143,463 (Nov 7, 2000), US 6,150,069 (Nov 21, 2000), US 6,180,316 B1 (Jan 30, 2001), US 6,225,020 B1 (May 1, 2001), US 6,235,448 B1 (May 22, 2001) and US 6235447 B1 (May 22, 2001).

Preferred photoacid generators have relatively low light absorbance in the wavelength of 157nm and 193nm. More preferred photoacid generator is phthalimidotrifluoromethane sulfonate, dinitrobenzyltosylate, n-decyl disulfone, naphthylimido trifluoromethane sulfonate or mixtures thereof.

The photoacid generator can further comprise a compound selected from the group consisting of diphenyl iodide hexafluorophosphate, diphenyl iodide hexafluoroarsenate, diphenyl iodide hexafluoroantimonate, diphenyl p-methoxyphenylsulfonium triflate, diphenyl p-toluenylsulfonium triflate, diphenyl p-isobutylphenylsulfonium triflate, diphenyl p-tert-butylphenylsulfonium triflate, triphenylsulfonium hexafluoroarsenate, triphenylsulfonium hexafluoroantimonate, triphenylsulfonium triflate, dibutyl naphthylsulfonium triflate and mixtures thereof.

Typically, the amount of photoacid generator ranges from about 0.05 to about 10% by weight of the photoresist polymer employed. It has been found that when the photoacid generator is used in the amount less than about 0.05%, it lowers photosensitivity of the photoresist composition, and when the photoacid generator is used in the amount greater than about 10%, it results in a poor pattern formation due to its high absorption.

On the other hand, any of conventional organic solvent can be employed for this invention and some of the conventional one are also disclosed in the documents described above. Preferred organic solvents for

photoresist composition is methyl 3-methoxypropionate, ethyl 3-ethoxypropionate, propylene glycol methyl ether acetate, cyclohexanone, 2-heptanone, ethyl lactate or mixtures thereof.

The amount of organic solvent ranges from about 500 to about 2000% by weight of the photoresist polymer to coat the photoresist in a wanted thickness. It has been found that when the organic solvent is used in the amount of 1000wt%, a thickness of the photoresist is about 0.25 μ m.

The present invention also provides a process for forming a photoresist pattern comprising:

(a) coating the photoresist composition described above on a substrate to form a photoresist film;

(b) exposing the photoresist film to light; and

(c) developing the exposed photoresist film to obtain a photoresist pattern.

The process for forming the photoresist pattern can further include a soft baking which is performed before the step (b) and/or a post baking step which is performed after the step (b). Preferably, the soft and post baking steps are performed at temperature in the range from about 70 to about 200°C.

Exemplary light sources which are useful for forming the photoresist pattern include not only VUV but also ArF, KrF, E-beam, EUV or ion beam. Preferably, the irradiation energy in the step (b) is in the range between about 1mJ/cm² and about 100 mJ/cm².

On the other hand, the step (c) can be performed in alkaline developing solution which is preferably TMAH

aqueous solution with a concentration ranging from about 0.01 to about 5wt%.

In addition, a semiconductor device can be manufactured using the photoresist composition described above.

The disclosed polymers and photoresist compositions will now be described in more details by referring to examples below, which are not intended to be limiting.

10 I. Preparation of Photoresist Polymers

Example 1--Synthesis of poly(hexafluorocyclobutene/2-methyl 2-adamantyl 5-norbornene-2-carboxylate)

To 20mL of anhydrous tetrahydrofuran was added
15 hexafluorocyclobutene (0.1mole), 2-methyl 2-adamantyl 5-norbornene-2-carboxylate(0.1mole) and AIBN(0.3g), and was passed through nitrogen thereby removing general air. And the resulting solution was shielded thoroughly and reacted at about 90°C for about 10 hours. Thereafter, a
20 polymer was precipitated and filtered in mixture solution of methanol and water, thereby obtaining the entitled compound (yield : 35%).

Example 2--Synthesis of poly(octafluorocyclopentene/8-ethyl 8-tricyclodecanyl 5-norbornene-2-carboxylate)

To 20mL of anhydrous tetrahydrofuran was added
octafluorocyclopentene (0.1mole), 8-ethyl 8-tricyclodecanyl 5-norbornene-2-carboxylate(0.1mole) and AIBN(0.3g), and was passed through nitrogen thereby
30 removing general air. And the resulting solution was shielded thoroughly and reacted at about 90°C for about 10 hours. Thereafter, a polymer was precipitated and

filtered in mixture solution of methanol and water,
thereby obtaining the entitled compound (yield : 36%).

Example 3--Synthesis of
poly(octafluorocyclopentene/2-methyl 2-adamantyl 5-
5 norbornene-2-carboxylate/2-ethyl 2-adamantyl acrylate)

To 20mL of anhydrous tetrahydrofuran was added
octafluorocyclopentene (0.05mole), 2-methyl 2-adamantyl
5-norbornene-2-carboxylate(0.05mole), 2-ethyl 2-adamantyl
acrylate(0.05mol), and AIBN(0.3g), and was passed through
10 nitrogen thereby removing general air. And the resulting
solution was shielded thoroughly and reacted at about 90°C
for about 10 hours. Thereafter, a polymer was
precipitated and filtered in mixture solution of methanol
and water, thereby obtaining the entitled compound
15 (yield : 39%).

Example 4--Synthesis of
poly(hexafluorocyclobutene/4-ethoxyethoxy styrene/4-
hydroxy styrene)

(Step 1) Synthesis of poly(hexafluorocyclobutene/4-
20 acetoxy styrene)

To 20mL of anhydrous tetrahydrofuran was added
hexafluorocyclobutene (0.1mole), 4-acetoxy
styrene(0.15mole) and AIBN(0.3g), and was passed through
nitrogen thereby removing general air. And the resulting
25 solution was shielded thoroughly and reacted at about 90°C
for about 10 hours. Thereafter, a polymer was
precipitated and filtered in mixture solution of methanol
and water, thereby obtaining the entitled compound
(yield : 56%).

30 (Step 2) Synthesis of poly(hexafluorocyclobutene/4-
hydroxy styrene)

To mixture solution which is 20mL of methanol and
30mL of 1N hydrochloric acid was added
poly(hexafluorocyclobutene/4-acetoxy styrene) obtained in

Step 1(0.05mole). And the resulting solution was reacted at about 50°C for about 10 hours, thereby obtaining the entitled compound (yield : 95%).

5 (Step 3) Synthesis of poly(hexafluorocyclobutene/4-ethoxyethoxy styrene/4-hydroxy styrene)

To 10mL of tetrahydrofuran was added poly(hexafluorocyclobutene/4-hydroxy styrene) obtained in Step 2(0.04mole) and sulfuric acid(0.1mL), and the resulting solution was stirred at room temperature for
10 about 10 minutes. And then ethylvinylether was injected a reactor containing the resulting solution and stirred for about 10 hours. Thereafter, a polymer was precipitated and filtered in mixture solution of methanol and water, thereby obtaining the entitled compound substituted some
15 hydrogens of hydroxyl group with ethoxyethyl which is acid labile protecting group (yield : 92%).

II. Preparation of Photoresist Compositions and Formation of Patterns

20 Example 5--Preparation of Photoresist Compositions and Formation of Patterns(1)

To 50g of propylene glycol methyl ether acetate(PGMEA) was added 5g of the photoresist polymer obtained in Example 1, 0.03g of
25 phthalimidotrifluoromethane sulfonate, and 0.03g of triphenylsulfonium triflate. The polymer was precipitated and filtered in 0.20μm filter to obtain a photoresist composition.

The photoresist composition thus prepared was spin-coated on silicon wafer to form a photoresist film, and
30 soft-baked at about 110°C for about 90 seconds. After baking, the photoresist was exposed to light using a ArF laser exposer, and then post-baked at about 110°C for

about 90 seconds. When the post-baking was completed, it was developed in 2.38wt% aqueous TMAH solution for about 40 seconds, to obtain 0.12 μ m L/S pattern (see Figure 1).

Example 6--Preparation of Photoresist Compositions and Formation of Patterns(2)

To 70g of propylene glycol methyl ether acetate(PGMEA) was added 10g of the photoresist polymer obtained in Example 2, 0.06g of phthalimidotrifluoromethane sulfonate, and 0.06g of triphenylsulfonium triflate. The polymer was precipitated and filtered in 0.20 μ m filter to obtain a photoresist composition.

The photoresist composition thus prepared was spin-coated on silicon wafer to form a photoresist film, and soft-baked at about 110°C for about 90 seconds. After baking, the photoresist was exposed to light using a ArF laser exposers, and then post-baked at about 110°C for about 90 seconds. When the post-baking was completed, it was developed in 2.38wt% aqueous TMAH solution for about 40 seconds, to obtain 0.12 μ m L/S pattern (see Figure 2).

Example 7--Preparation of Photoresist Compositions and Formation of Patterns(3)

To 70g of propylene glycol methyl ether acetate(PGMEA) was added 10g of the photoresist polymer obtained in Example 3, 0.06g of phthalimidotrifluoromethane sulfonate, and 0.06g of triphenylsulfonium triflate. The polymer was precipitated and filtered in 0.20 μ m filter to obtain a photoresist composition.

The photoresist composition thus prepared was spin-coated on silicon wafer to form a photoresist film, and soft-baked at about 110°C for about 90 seconds. After baking, the photoresist was exposed to light using a ArF

laser exposer, and then post-baked at about 110°C for about 90 seconds. When the post-baking was completed, it was developed in 2.38wt% aqueous TMAH solution for about 40 seconds, to obtain 0.12μm L/S pattern (see Figure 3).

5 Example 8--Preparation of Photoresist Compositions and Formation of Patterns(4)

To 70g of propylene glycol methyl ether acetate(PGMEA) was added 10g of the photoresist polymer obtained in Example 4, 0.06g of
10 phthalimidotrifluoromethane sulfonate, and 0.06g of triphenylsulfonium triflate. The polymer was precipitated and filtered in 0.20μm filter to obtain a photoresist composition.

The photoresist composition thus prepared was spin-
15 coated on silicon wafer to form a photoresist film, and soft-baked at about 110°C for about 90 seconds. After baking, the photoresist was exposed to light using a ArF laser exposer, and then post-baked at about 110°C for about 90 seconds. When the post-baking was completed, it
20 was developed in 2.38wt% aqueous TMAH solution for about 40 seconds, to obtain 0.12μm L/S pattern (see Figure 4).

Experimental Example--Examination of Absorbance at 157nm

Absorbance of photoresist composition obtained in
25 Example 8 coated in a thickness of 2500Å was shown by VUV spectrum of Figure 5. According to Figure 5, the absorbance of the photoresist composition of Example 8 at 157nm wavelength was 0.18, which was merely a third of the absorbance of conventional photoresist for KrF or ArF
30 light source at 157nm. Thus, the conventional photoresist composition should be coated in a thickness of 600~700Å or less to satisfy the requisite of light transmittance for a lithography process employing 157nm light source,

while the photoresist composition according to the present invention, having high light transmittance for 157nm light source, can provide efficient pattern even when it coated in a thickness of 1500 Å or more.

5 The photoresist composition according to the present invention ensures enhanced etching resistance, as it allows formation of photoresist film in a sufficient thickness.

10 From Experimental Example, it is noticed that the composition comprising the photoresist polymer according to the present invention has excellent light transmittance at 157nm wavelength, so that it can be usefully employed for a photolithography process using 157nm light source. In addition, from Examples 5 to 8, it is ascertained that the photoresist composition comprising the photoresist polymer according to the present invention has effective physical property as a photoresist.

20 As discussed earlier, a photoresist pattern having excellent durability, etching resistance, and developable property can be formed successfully by employing the photoresist composition of the present invention. And the photoresist composition of the present invention can be used in forming a minute pattern below 1G DRAM as well as 4G and 16G. Moreover, the photoresist polymer of the present invention has a low light absorbance at the 157nm wavelength, and thus is suitable for a photolithography using VUV.